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Dynamic thinking about food system vulnerabilities in highly developed countries: Issues and initial analytic structure for building resilience

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Abstract

This paper presents the first step in applying a system dynamics analysis to the question of food system vulnerability and resilience in developed countries. Existing literature and models about food security largely focus either on effects of climate change on agriculture at a global scale or on specific issues on a regional scale, most often in food insecure countries. While there has been considerable attention in highly developed countries to specific issues such as organic food, agribusiness, effects of pesticide and fertilizer runoff, or introduction of genetically modified organisms, it is hard to get a clear picture of the ways in which the food system as a whole is vulnerable and resilient at the national level. Here we synthesize literature about food systems and discuss differences in food systems between less developed and highly developed countries. Based on the literature review, we develop a conceptual model. We describe next steps for developing an operational model for raising awareness of vulnerability and resilience in developed country food systems.

Introduction

Food system vulnerability and resilience in highly developed countries have not been much studied from a national-level, whole-system perspective, especially for more developed tries. Most of the literature on food systems focuses on food insecure countries, with good reason. Worldwide, over 850 million people do not have regular access to the minimum calories they require on a regular basis, and most of those are in Asia and sub-Saharan Africa (Hammond & Dubé, 2012). Population growth, changing consumption patterns, increasing pressures on land for uses other than agriculture and changing climatic conditions threaten food supplies (Godfray et al. 2010a). Further, significant impacts of climate change are expected on smallholder farmers because of their limited access to adaptive technology and agricultural practices (Muller et al. 2011). A number of studies have examined different aspects of food security in developing countries (e.g., Quinn 2002, Bach and Saeed 1992 (Vietnam), Bala 1999 (Bangladesh), Coxhead 2000 (Phillippines), Falcon et al. 2004 (India), Holden et al. 2005 (Ethiopia)).

On the global level, the literature about food security primarily concerns effects of climate change on crop production (e.g., Rosenzweig and Parry 1994, Schmidhuber and Tubiello 2007). Rosenzweig et al. (2013) describe the AgMIP project, which links climate change models with crop production and economic models to examine potential effects on food supply in different regions. Other studies have examined the role of global trade (e.g., Rosegrant et al. 2005). Schmidhuber and Tubiello (2007) point out, however, that food security is more than just ensuring a sufficient food supply. It also is a function of stability of food supplies, access (resources or other means to get food), and utilization of food resources (ability to use food effectively, which is affected by health conditions.)

In more developed countries, discussions about food systems focus more on food-related health issues such as obesity and malnutrition than on hunger (Hammond & Dubé, 2012). The U.S. has long had a high and growing rate of obesity, but other countries such as Australia, U.K., and China are also showing similar alarming trends, to the degree that the world’s overweight and obese population now exceeds the world’s underweight population (Popkin 2006; Popkin 2010). Other issues in the literature include managing greenhouse gas emissions from the food chain (Garnett 2011), evaluating whether the movement toward local food sources promotes environmental health (Edwards-Jones 2010), how convenience stores affect food choices (Sharkey et al. 2013), and how consumption patterns affect land use requirements (Gerbens-Leenes and Nonhebel 2002). There is a lack of system-wide analysis of the links and feedback mechanisms between different aspects of the food system.

The aim of this paper is to establish a framework for critically analyzing system vulnerabilities, opportunities to build resilience and tradeoffs between policy options to promote resilience. In developed countries, consumers in the system have the potential to influence system resilience through their choices, so one goal is to present a system-wide perspective for communicating system tradeoffs to the general public. Another goal is to illuminate potential vulnerabilities that might require national policy interventions.

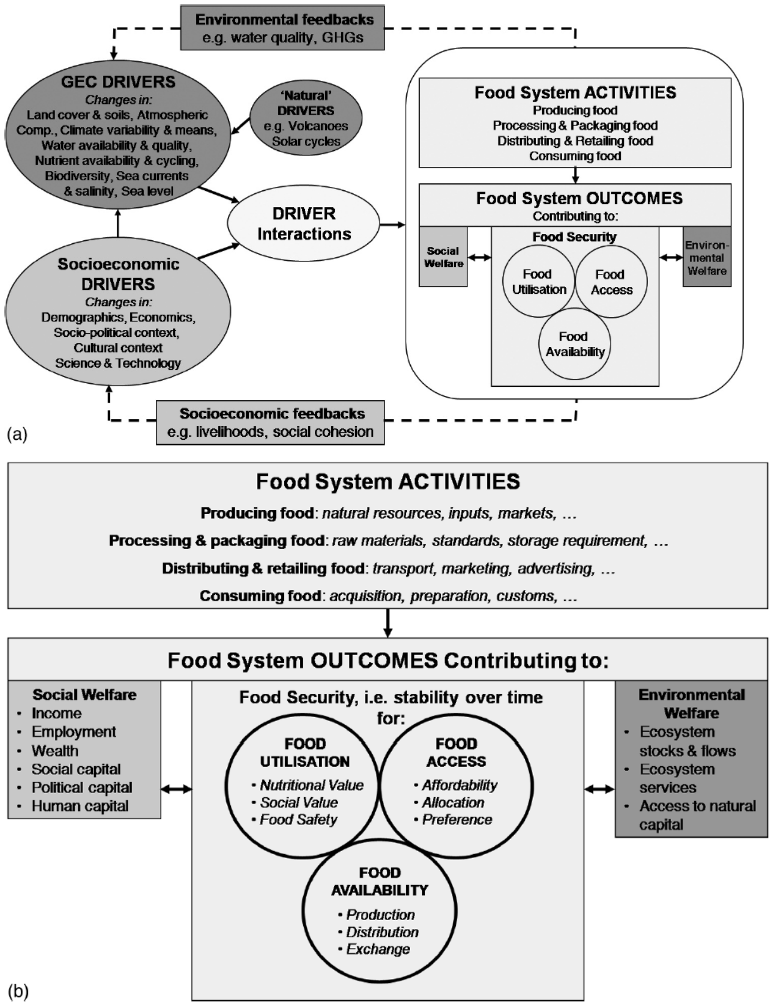
For this purpose, we review the literature about food system issues, differences between developing and more developed country food systems, concepts of vulnerability and resilience, existing models, and food system structure to distill an initial causal structure. We then describe the framework for developing a simple operational model from this structure and the questions to be examined.

Structure and Vulnerability of Food Systems in Developed Countries

Food systems, at a minimum, comprise the sets of activities involved in food production; processing and packaging; distribution and retail; and consumption (Ericksen, 2008). Each of these activities is influenced by, and influences a range of social, economic, political, health and environmental factors such as agricultural technology, land ownership, capital markets, infrastructure, distribution of disease, access to clean water, and social norms and practices related to hygiene and food preparation (Hammond & Dubé, 2012; Muller et al. 2011). Activities cross multiple levels of scale, from individual producers (farmers) and consumers to regional, national, international markets, and global supply chains. Agri-food systems with their respective food system activities are the manifestations of political, biophysical, socioeconomic and other drivers that lead to sustainable or unsustainable outcomes, depending on the perspectives, scales, valuations of trade-offs and time frames considered (Neufeldt et al., 2013).

A food system can be conceived as including the determinants and outcomes of its activities. The determinants describe the bio-geophysical as well as the social, economic and political environments that determine how food system activities are performed (food system drivers). These activities lead to a number of social, environmental and food security outcomes. Food system activities and outcomes eventually result in processes that feed back to environmental and socioeconomic drivers (Ericksen, 2008; FAO, 2008; cf. Figure 1).

Figure 1: Food systems, their drivers and feedback (a); components of food systems (b) (Ingram et al., 2010: 28)



While the basic structure of food systems is similar everywhere – food is produced, processed, distributed, and consumed – the details are considerably different between developing and developed countries. The length of the food chain is greater in developed than developing countries, production depends more on technology and external inputs of fertilizers and pesticides in developed countries and more on labor in developing countries, there is more diversity in foods available for consumption in more developed countries, and more highly developed countries consume more meat, for example. Godfray et al. (2010b) note that 30-40% of food in most countries is lost to waste, but where the waste occurs is different. In developing countries, most is lost on the farm and in transport/processing, while in more developed countries, most is wasted after initial processing, in retail, food service, and homes and municipalities (Gustavsson et al., 2011). Reducing waste thus requires different strategies. In the developing world, better storage and transport technologies would help, while in developed countries, waste reduction may require changes to food expiration date regulations, or education to change food handling behavior or consumer attitudes.

Other differences include the relative importance of energy for storage and distribution, effects of pesticide and fertilizer use on the environment, and consumer preferences. In the U.S., as distribution networks have increased, the amount of storage has decreased, raising questions about the effect of a prolonged fuel shortage or disruption in transportation. By one estimate, the population of Hawaii needs 2,000,000 meals-ready-to-eat (MREs) to survive one month without electricity but the emergency management agency in the state has only 35,000 stored (Marten, pers. comm.). Greater emphasis on local food sources is being promoted as a solution to what some consumers perceive as too great a separation between themselves and the source of their food (Seyfgang 2006). Decreasing 'food-miles' is thought to increase food quality and decrease environmental pollution. However, decreasing food-miles may not have the benefits envisioned (Edwards-Jones 2010, Edwards-Jones et al. 2008), and may even have unintended negative consequences. Food system analysts in Australia are concerned that shifts to local food sources may erode regional infrastructure and leave local communities vulnerable if local sources fail (Larsen, pers. comm.). In Switzerland, where a large part of the calories consumed are imported, changes to consumption patterns can have far-reaching impacts (Kopainsky et al., under revision).

Compared with the problem of providing enough food to people in food insecure parts of the world, food system issues in the developed world seem at first glance to be less significant. But complex connections between food storage, food-miles, nutrition, and environmental and human health raise questions about how the system might respond to different kinds of disturbances such as climate change, energy shortage, prolonged water stress, pest infestation or animal disease, or pandemic. Another key challenge is that of aligning food security outcomes (e.g., providing the population with at minimum sufficient and at maximum desired amounts of food) with environmental outcomes (e.g., enhancing and maintaining the provision of ecosystem services). This challenge is exacerbated by processes such as intensification, specialization, distancing and concentration/homogenization, which make it difficult to relate concerns about the quality of food and about environmental risks to consumer choices and to food production methods (Sundkvist et al., 2005).

Vulnerability of a food system is a function of exposure, sensitivity and adaptive capacity (Ericksen et al., 2010). Food systems can be vulnerable to a variety of stressors (Adger, 2006; Leichenko & O'Brien, 2008), and they often constitute a combination of environmental stresses and institutional as well as policy failures. Analyzing the vulnerability of an agricultural region fails to adequately capture the complex spatial and temporal interdependencies and feedbacks that determine how food security outcomes are achieved. Attention is thus required not only on the vulnerability of food availability but also of food access and utilization (Eakin, 2010). For example, this implies devoting attention to the vulnerability of food storage, processing, distribution and retailing, as these activities link production and consumption across space and time (Eakin, 2010). In the USA, for example, the railway system and sea ports are thought to be vulnerable to a variety of climatic disturbances, including flooding, increased severe hurricane activity and sea-level rise (NRC, 2008).

In this analysis, we examine the kinds of disturbances to which developed country food systems are most vulnerable, how might they be made more resilient to those disturbances, and what potential unintended consequences might result from popularly advocated policies such as greater localization of food sources.

Resilience thinking has its origin in ecology (Holling, 1973) but has since been expanded to social-ecological systems (Adger, 2000; Adger et al., 2005; Carpenter et al., 2001; Folke, 2006). Resilience can be defined as the 'capacity of a system to experience shocks while retaining essentially the same function, structure, feedbacks, and therefore identity' (Walker et al., 2006). Resilience is alternatively used to describe the disturbance that can be absorbed before a change in state (e.g., Holling, 1996) or the rate of recovery from perturbation (e.g., Adger, 2000). Resilient systems are less vulnerable to stressors.

In system dynamics terms, we might characterize the resilience of a food system, or a portion of the food system, by examining the stocks. Any given stock might be sustainable if the flows in and out of the stock are the same. A high level of food available for distribution, or a high level of food storage can be maintained by managing the inflows and outflows to match each other. But that sustainable condition can also be met with low levels in the stock. A disturbance to the system might be represented by a sudden, large change to the outflow. For example, a failure in the electricity grid that affected food storage cooling systems in a way that some portion of food in storage that's perishable is spoiled. If the disturbance occurred with a large amount of food in storage, the sudden increase in outflow might reduce the amount significantly, but still leave food available to be consumed. If the system is being maintained with a very low level of stored food, however, a shock might decrease this to zero, which then might increase the number of deaths in the population, potentially decreasing the labor force and ultimately decreasing the amount of food we could continue to produce. These different conditions for sustainability have different implications for the resilience of the system to withstand a shock to the system.

Existing Food System Models

While the food system representation in Figure 1 gives a conceptual overview of the key sectors involved in food systems, it fails to explicitly illustrate the feedback mechanisms that might lead to counterintuitive system responses to initiatives such as local food movements or how food storage issues might make the system vulnerable to particular disturbances. Here we briefly review efforts to model food system dynamics and then discuss how system dynamics tools can add value to modeling efforts.

Existing models of large-scale food systems, i.e., at the national or global level, incorporate few, if any, feedback mechanisms. Decision support tools such as general equilibrium models or optimization models are widely used for an integrated analysis of the environmental and (socio-) economic impacts of development trends and policy interventions in SES (Janssen et al., 2011; Rossing et al., 2007; Schlüter et al., 2012). These tools allow for the simultaneous assessment of environmental and economic impacts in different sub-systems and over time to capture dynamics and emerging trade-offs. The IIASA Basic Linked System (BLS) model presents one major effort to link national agricultural systems with each other to examine how they affect one another (Fischer et al. 2002). The BLS model is a general equilibrium model. It does include some environmental factors such as variables that are affected by climate change. However, there is no feedback from the economic part (production amount and value) to the environment and this is a limitation for the purpose of examining vulnerabilities and tradeoffs within a given national system.

Other approaches for agricultural sector modeling are Life Cycle Assessment, Material Flow Analysis, and Environmentally Extended Input-Output Models (Minx et al., 2009; Stoessel et al., 2012; Carlsson-Kanyama & Gonzalez, 2009; Corson & van der Werf, 2012; Jungbluth, 2000; Nemecek & Gaillard, 2008; Xue & Landis, 2011). While these provide a detailed overview of physical as well as economic flows and dependencies, they do not explicitly represent the agricultural production processes. A wide range of agricultural sector modeling studies address the effects of policy changes in Switzerland on agricultural production. These studies demonstrate the complex interactions between farm decision-making and environmental outcomes at the sectoral or farm gate level (Briner et al., 2012; Huber et al., 2013; Schüpbach et al., 2008). However, these studies do not take into account the environmental and economic impact in the supply chains of agriculture.

Simulation models such as agent-based models and system dynamics offer powerful tools to model food systems interactions and feedbacks (Hammond & Dubé, 2012). Simulation models help unraveling the complex and dynamic interactions and feedbacks among biophysical, socio-economic and institutional components across levels and scales (Dent et al., 1995; Feola et al., 2012; Janssen & van Ittersum, 2007; Schiere et al., 2012). *Agent based modeling* approaches are widely used to model social-ecological systems such as food systems (Heckbert et al., 2010; Huber, et al., 2013; Le et al., 2010; Le et al., 2008; Le et al., 2012; Li, 2011; Miller & Page, 2007; Schlüter, et al., 2012; Tesfatsion & Judd, 2006). By representing flexible feedback loop structures (built on emerging interactions rather than fixed cause-effect relationships) across levels, the approach is valuable for explaining structural/organizational adaptation to changes in system drivers. Though the technique can theoretically address cross-scale interactions, it is still challenging to do so due to excessive data requirements.

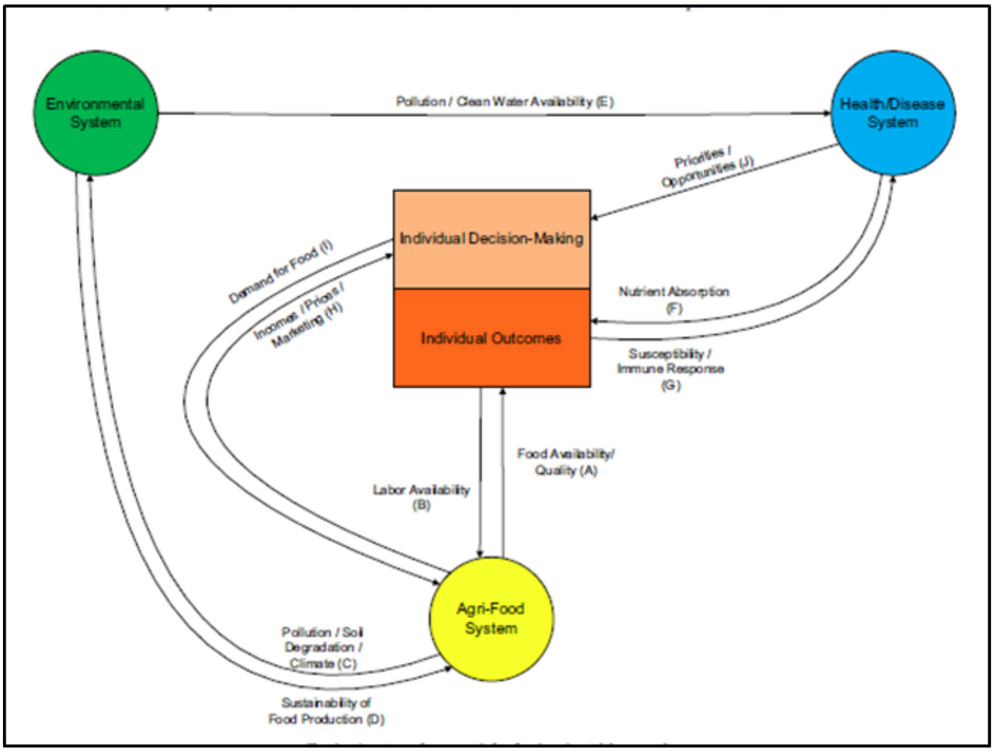
A growing body of literature studies transformation processes in the agri-food system resulting from different policy interventions and the interaction of different stakeholders following a *system dynamics* approach (Belcher et al., 2004; Georgiadis et al., 2005; Jones et al., 2002; Kopainsky et al., 2012; Saysel & Barlas, 2001; Saysel et al., 2002; Shi & Gill, 2005).

Causal Structure of a System Dynamics Model

Hammond & Dubé, (2012) propose a high-level conceptual systems model linking the agri-food sub-system with the environmental and health sub-systems through individual choices and outcomes (Figure 2). Their model examines effects of these three systems on individual decisions (such as work, food choices) and individual outcomes (such as health and economic status).

The main processes in the agri-food (production of raw food materials, processing and packaging for consumption*,* distribution, use by consumers) are affected by influences from other sub-systems and contain reinforcing feedbacks such as: poor nutrition → poor health → decrease in nutrient absorption → poor nutrition.

Figure 2: A systems framework for food and nutrition security (Hammond & Dubé, 2012: 2)

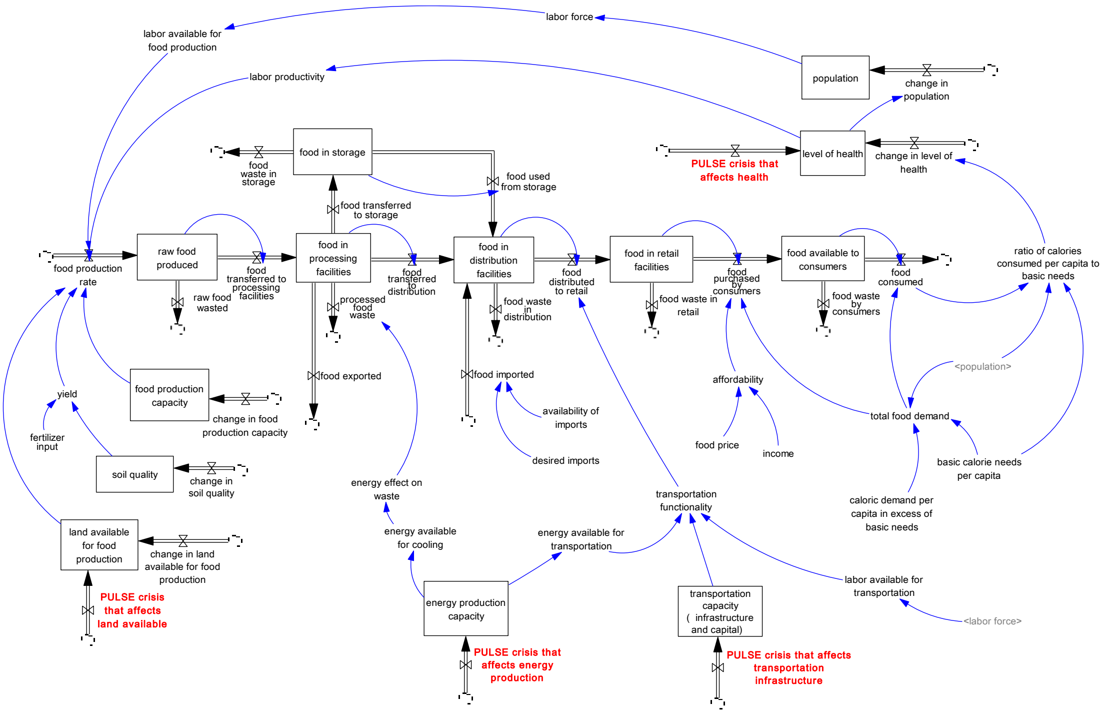


Muller et al. (2011) suggest the following key elements that should be part of a comprehensive food systems model.

- System structural issues that might affect vulnerability and resilience include: the length of the food supply chain, connection to global demand and supply patterns and trade, input requirements of the agricultural value chain, degree of centralization of the food system, existing climate variability, existing mechanisms to cope with variability, types and diversity of cropping systems, efficiency of market access.
- Some of the likely stresses on the system beyond climate change include population growth and shifting patterns of food intake due to urbanization and development. Indirect effects of climate change and other stressors include changes in pests and pathogens.
- Possible adaptations include changing the types of agricultural production (from livestock to crops, or from crops to trees) or changing agricultural inputs required. They suggest tradeoffs be explored between agricultural expansion, intensification and trade.

Figure 3 shows an initial stock and flow structure that aims to simplify the system as much as possible for explanatory purposes while still incorporating key components. It also identifies entry points for disturbances that increase vulnerability. Thus, it provides an initial representation of system structural issues and of some of the likely stresses from the list above.

Figure 3: Initial stock and flow structure exploring structural issues of and stresses on food systems



Notes:

Variables in red: sources of vulnerability

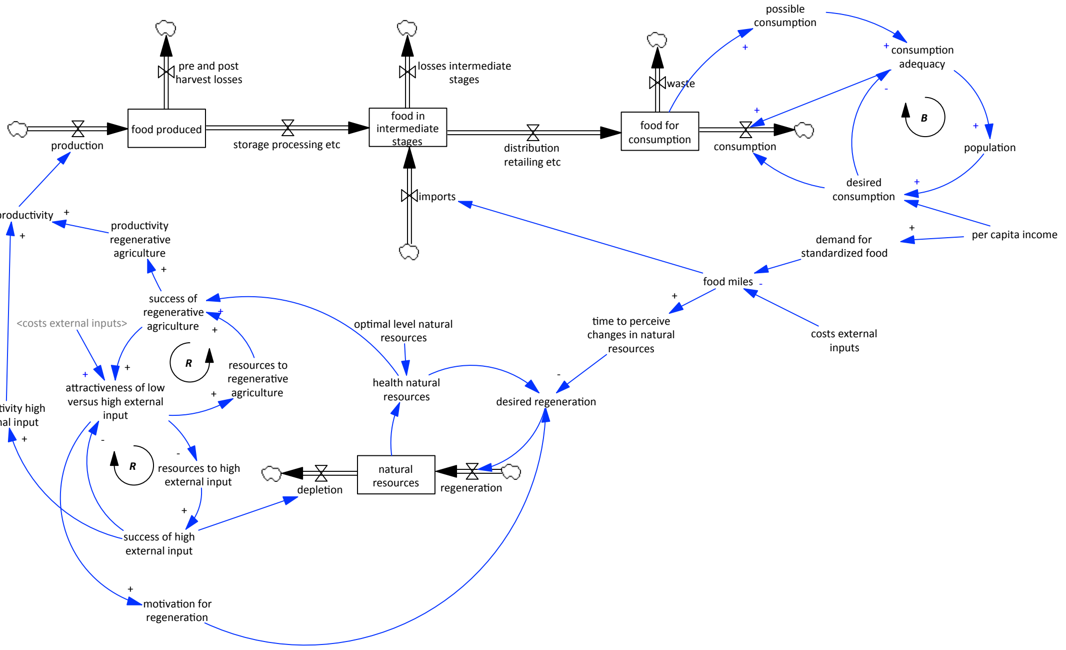
The stock and flow structure in Figure 3 shows the following entry point for disturbances or stressors (representing sources of vulnerability):

- Energy prices/fossil fuel prices (e.g. “PULSE crisis that affects energy production”): These stressors on the one hand affect the high external input farming systems with their high reliability on mineral fertilizers and labor-saving mechanization and on the other hand the transportation costs involved in moving food and food products from one food system activity to the other, especially the movement of imported products.
- Disruptions of storage, processing and transportation infrastructures (e.g., “PULSE crisis that affects transportation infrastructure”). Such disruptions affect the movement of food and food products from agricultural production to consumers. The length of a supply chain can increase their vulnerability to global disruptions. Entirely local supply chains on the other hand can be vulnerable to local disruptions. Effective supply chains thus rely on diversity in the length and kind of supply chains.
- Destruction of productive resources resulting from, e.g., droughts or floods (e.g., “PULSE crisis that affects land available”).
- Indirect effects of climate change such as changes in pests and pathogens affect the success of the two main farming systems differently. The diversity inherent in low external input farming systems makes it more likely that the farming system can cope with such changes.
- Stresses on the system beyond climate change include population growth and changes in consumption patterns but also the potential impacts of pandemics and other disturbances on the availability of agricultural labor force necessary for (domestic) production (e.g., “PULSE crisis that affects health”).

In addition to these exogenous sources of vulnerability, the representation of a food system in terms of stocks and flows indicates additional sources of vulnerability. Reliable provision of food for a more demanding and potentially growing population requires food to move through the various stocks in the food system, that is, from the stock of raw food produced all the way to food available to consumers. The reliability of this process not only depends on the flows linking the various stocks but also on the average residence time of food in each of the stocks. Low residence times indicate fast movements of food through the chain. This makes the food system efficient as long as flows are left uninterrupted. Low levels of stocks, however, can affect food provision very negatively in situations where inflows are interrupted or stocks are depleted in the course of environmental, economic and social shocks.

A key challenge for national food systems in developed countries is that of aligning food provision with environmental welfare. Figure 4 aggregates the stock and flow structure from Figure 3 but adds a series of mechanisms that explain the relationships between food provision and environmental welfare. It picks up the third element of a comprehensive food systems model from the list by Muller et al. (2011) by sketching initial structures for exploring tradeoffs in food systems.

Figure 4: Initial structure for exploring tradeoffs in food systems



Environmental welfare and food provision are driven, among others, by:

- A stock of productive resources such as land, water, nutrients, soil organic matter and plant genetic variety. In Figure 3, this stock was labeled “soil quality”. Here, we use a more generic term that includes a variety of productive resources. The level of this stock determines the health of natural resources and thus provides information about environmental welfare.
- The productivity of this stock, that is, the amount of food that can be produced with one unit of productive resources. For plant production, productivity is equivalent to yield. The total productivity variable provides information about the capacity of the agricultural system to produce food and thus information about food provision.

The flows affecting the stock of productive resources are determined, among other things, by the implemented agricultural production system. Agricultural production systems are characterized by the type and amount of external inputs necessary to support it, by its productivity, and by its environmental impacts. We differentiate between two main farming systems:

- High external input production systems: Commercial market orientation; Use of improved high-yielding varieties; Mechanization with low labor intensity; Almost complete reliance on external synthetic inputs (fertilizers, pharmaceuticals, etc.). High external input systems tend to overexploit, that is, degrade productive resources, e.g., through the dispersion of pesticides into the environment.
- Regenerative production systems: Largely subsistence focus and less market orientation; Use of traditional cultivars; High labor and knowledge intensive techniques; No or very little application of external nutrients, no use of synthetic chemicals for pest and disease control, but high emphasis of on-site nutrient cycling. Regenerative agricultural production systems tend to be characterized by diverse cropping systems that help rebuilding and maintaining stocks of productive resources.

The extent to which each production system is implemented follows the logic of the success to the successful archetype (Senge, 1990):

- The variables “resources to high external input”/”resources to regenerative agriculture” represent the potential yield of the two production systems.
- The variables “success of high external input”/”success of regenerative agriculture” represent the realization of the potential yield (with different polarities, the variables could also represent the remaining gap between realized and potential yield).

With the availability of cheap fossil fuel, external inputs such as fertilizer and pesticides have been used over the last decades to boost crop yields (Sundkvist, et al., 2005). The success of this high external inputs production paradigm reinforces itself and forces the alternative production paradigm, one that treats natural resources in a regenerative way, into a vicious cycle.

One of the problems with this success to the successful archetype is that once the costs of external inputs increase or if external inputs are not available at all, it takes a long time for the regenerative agriculture paradigm to be effective. The dominance of the high external input paradigm erodes the knowledge base necessary for a successful implementation and continuous adaptation of the regenerative agriculture paradigm. This indicates a hidden source of vulnerability of food systems and especially one for which it takes a lot of time and effort to build resilience.

The health of natural resources is a proxy for options for adaptation and alternative solutions in case of changes in the environment such as climatic shocks or pests and pathogens. Low health of natural resources indicates low diversity and diversity is important for absorption of shocks, adaptation and alternative solutions (Berkes et al., 2003).

It is important to note, however, that the attractiveness of low external input farming systems, especially under low-disturbance circumstances and as long as external costs are not internalized, is bounded by higher labor and product costs caused by the diversity of products and practices. The same applies to costs related to the diversity of processing and retailing facilities as well as the diversity of imports. There is thus an inherent tension or an inherent trade-off between the adaptive capacity characteristic for low external input farming systems and the efficiency characteristic for high external input farming systems (Darnhofer, Bellon, et al., 2010; Darnhofer, Fairweather, et al., 2010).

Policy Analysis

In this section, we interpret strategies proposed to foster the achievement of food security outcomes from the perspective of the conceptual model developed in the previous section.

The literature describes a variety of strategies proposed to meet the challenge of feeding an ever-growing population with growing consumption needs while protecting the natural resource base of agriculture and food systems (e.g., Foley et al., 2011 ; Godfray et al., 2010; Pretty et al., 2010; Tilman et al., 2002; Tilman et al., 2011). Such strategies include:

- Sustainable crop production intensification, that is, producing more from the same area of land while conserving resources, e.g., through the application of conservation agriculture practices, the use of good seed of high-yielding adapted varieties, integrated pest management, plant nutrition based on healthy soils, efficient water management, and the integration of crops, pastures, trees and livestock. This strategy is knowledge-intensive so that policies for sustainable intensification should build capacity through extension approaches (FAO, 2011).
- Increasing production limits, mostly through genetic modification of crop and livestock species.
- Reducing waste and losses.
- Changing diets.
- Expanding aquaculture.

In subsequent versions of this paper and based on a revised conceptual framework, we will be able to discuss in detail the dynamic implications of such strategies and to interpret them in terms of feedback loops and potential unintended consequences resulting from the interaction of these loops. Increasing production limits through either conventional breeding or genetic modification, for example, aims at increasing the potential yield. However, such strategy is depends on the availability of external inputs such as fertilizers, herbicides and pesticides. Our conceptual model shows that high external input farming systems degrade the stock of productive resources, which, in the long run, increases the vulnerability of the food system. This strategy is thus likely to result in better-before-worse behavior. It is also in itself vulnerable as its attractiveness is highly dependent on the costs and availability of external inputs.

Discussion and outlook

The objective of this paper was to develop a system dynamics model for raising awareness of the vulnerabilities of national food systems in developed countries and for identifying entry points for increasing their resilience. For this purpose, we synthesized the existing literature on food system frameworks and food system modeling into a conceptual model that describes the main causal structures responsible for the generation of food security and environmental welfare outcomes. Based on this dynamic representation of national food systems, we provided an initial discussion of the dynamic implications of various strategies proposed to improve food system outcomes. This discussion highlighted that the vulnerability of a national food system does not automatically results from exogenous shocks that might affect the country. Instead, it is either exacerbated or dampened by the interaction of the various feedback loops in the national food system. Thinking about the vulnerabilities of food systems therefore needs to go beyond an event-based view and include an endogenous representation of the processes governing national food systems.

In subsequent versions of this paper, we will further develop this line of research and describe next steps for developing an operational model that illustrates our current qualitative reasoning and quantifies the tradeoffs involved in reducing vulnerability and increasing resilience in developed country food systems.

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